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# PROCEEDINGS

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# WIND-LOAD STANDARDS IN EUROPE

By John W. T. Van Erp

STRUCTURAL DIVISION



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AMERICAN SOCIETY OF CIVIL ENGINEERS

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PAPERS

# WIND-LOAD STANDARDS IN EUROPE

By John W. T. Van Erp[1]

## Synopsis

As a result of a continued drive toward greater economy in structural design, wind-load standards have been more and more refined so that they agree almost exactly with actually occurring conditions. The task of the engineer is to proportion his design to fit the stipulated purpose of the structure with the utmost degree of economy while retaining the required factor of safety. The factor of safety covers a certain number of unknown quantities and it has been the constant endeavor of engineers to acquire a better understanding of these unknowns. Thus, on the one hand, analysis of the structure will have to yield stresses agreeing as closely as possible with those actually occurring whereas, on the other hand, the loads should be the expected ones with the least degree of exaggeration. It is imperative, therefore, that the designer have the best possible knowledge of loading conditions—the least information being available about wind loads. The fundamental dynamic character of wind loads must be translated into static equivalents to give simple data for the use of the designing engineer.

## Introduction

*1. History.*—For a number of decades, attempts have been made to formulate the forces exerted on structures by wind. From theoretical considerations, but mostly from tests, an often bewildering variety of data has been obtained. To make such data applicable to purposes of practical design, simplification and condensation into a concise set of rules have been attempted in different countries. These rules, in turn, have been the subject of various publications, and finally have emerged in new standards. It is worthwhile to review their most salient points. In most building codes in the United States, obsolete conceptions of wind load still prevail; and cases of damage from wind

Note.—Written comments are invited for publication; the last discussion should be submitted by May 1, 1951.

[1] Structural Engr., George A. Fuller Co., New York, N. Y.

recur far too frequently. Although windstorm damage can never be eliminated entirely, a better understanding of all the aspects of the phenomenon of wind load will certainly help to reduce the regular manifestation of its disastrous effects.

One of the first standards, complete with detailed shape coefficients, was fixed in an explicit and practical form in the Netherlands.[2] That this standard should have originated in that fuel-scarce and flat country is understandable, for handling the wind has been a tradition for centuries. In former times, the wind was utilized as a propellent force for ships, or as the motive power for windmills; in modern days the emphasis has been toward a more thorough understanding of its nonbeneficial effect as a loading condition on buildings.

Older codes, although differing in detail, were essentially the same in that they assumed that wind load caused only pressures on the windward side. They specified the following formulas for the calculation of those pressure forces, perpendicular to the surface: For plane surfaces normal to the wind,

$$W_n = p\,A \qquad (1)$$

in which $p$ is the pressure per unit of area; $A$ is the area; and $W$ is the total wind force, normal to the exposed surface. For plane surfaces, inclined at an angle $\alpha$ against the wind,

$$W_n = p \sin \alpha \, A \qquad (2a)$$

according to other codes,

$$W_n = p \sin^2 \alpha \, A \qquad (2b)$$

or, in America, the widely used Duchemin formula,

$$W_n = p \frac{2 \sin \alpha}{1 + \sin^2 \alpha} A \qquad (2c)$$

Neither Eq. 1 nor Eqs. 2 gave results that could be corroborated in actual experience. According to these formulas, for instance, a horizontal roof would receive no pressure; and no suction was indicated on any surface, under any condition. Modern analysis requires an approach to the problem from quite a different angle.

In view of the complicated pattern of pressure distribution on an arbitrary structure, the first simplification one must make is the division of the total force into a single force for each separate surface or plane. Assume a uniform pressure per unit of area for a given surface. This pressure is determined by two factors—velocity and shape coefficient.

*2. Velocity Pressure.*—Let $q$ be the pressure exerted on the center of a large plate by the moving air stream, perpendicular to its direction, where the velocity is zero. This "velocity pressure" varies with the following factors: $t$ equal to time; $y$ equal to the height aboveground; and $\beta$ equal to the direction of wind. The velocity pressure $q$ can be expressed as a general function of these factors, thus:

$$q = f(t, y, \beta) \qquad (3)$$

[2] "Windbelasting op Bouwwerken," by R. L. A. Schoemaker and I. Wouters, *Het Bouwbedrijf*, No. 22, 1932, p. 3.

*3. Shape Coefficient.*—The symbol $c$ denotes a dimensionless number, being a function of: $K$ equal to a symbolic parameter, dependent on the shape of the structure; $D$ equal to a scalar dimension of the structure; $k/D$ equal to a roughness factor, when $k$ is the average height of a single protuberance of the surface; $v$ equal to the wind velocity; $\rho$ equal to the density of the air; and $\mu$ equal to the viscosity of the air. Using these symbols the Reynolds number can be expressed as

$$\mathbf{R} = \frac{D\,v\,\rho}{\mu} \qquad (4)$$

and $c$ can be expressed as a general function of these factors; thus:

$$c = f\left(R, \frac{k}{D}, K\right) \qquad (5)$$

By application of Eqs. 3 and 5, the wind force on each surface—

$$W_n = c\,q\,A \qquad (6)$$

—can be determined. The total wind force on the structure is the summation of the forces on each plane; therefore the key formula for the final determination of wind load is

$$W = \Sigma W_n = \Sigma(c\,q\,A) \qquad (7)$$

## Velocity Pressure

*4. Velocity-Time Relation.*—The main characteristic of the wind in nature is that it does not occur like a steady stream of air in a wind tunnel, but in gusts, which could be defined as the ratio of the maximum air velocity to the average air velocity. The air moves with an ever-changing velocity and direction, which cannot be reproduced accurately in model tests. Thus, the velocity of the average main stream of the natural wind is not uniform. The accelerating and decelerating movement of air therefore must be translated into a statically equivalent load.

Gusts can be classified into three types: (1) Those with very small-scale turbulence in the finer structure of the wind; (2) medium-sized frictional eddies, caused by roughness of surface of objects; and (3) large-scale gusts. Of these three, the large-scale gusts are the only ones that need to be regarded as exerting forces of significant magnitudes, and among these it is particularly the maximum gust that must be considered. The basic velocity pressures which are of importance for present purposes, therefore, will be quite different from those obtained from metereologically observed velocities. Such observations yield values only as transcribed by instruments, which generally have a considerable factor of inertia, so that the actual instantaneous maxima are not indicated; nor is the extent of the gust, vertically and horizontally. The absolute maximum velocities in wind gusts increase with height, but less than does the average wind velocity. This fact is recognized in the decreasing gust factor specifically mentioned and incorporated in the design wind pressures sponsored by the American Standards Association (ASA).[3]

[3] "Building Code Requirements for Minimum Design Loads in Buildings and Other Structures," *ASA–A58.1–1945*, p. 20, 5-1(c).

Wind gusts are caused by the unevenness of the surface of the earth and of the objects on it, or by the instability of the streaming air, demonstrating itself in line squalls or superadiabatic gradients. They are also created when air of greater elevations penetrates lower altitudes, retaining to a great extent its higher velocity. These are some of the reasons for the discrepancy between the shapes of the different curves shown in Fig. 1. In other words, each curve represents at least a threefold compromise between the metereologically observed maximum velocities, the velocity-height ratio, and the "gust factor" considered necessary by the authority from which the curve originates. When superadiabatic gradients occur, vertical movement of air will result; but its velocity is not high enough to demand consideration, and the direction of the wind can be taken as horizontal for most purposes. Where this condition does not hold true (as, for instance, for open sheds without walls), the exception should be considered as a different possible case of wind load, as in Table 1.

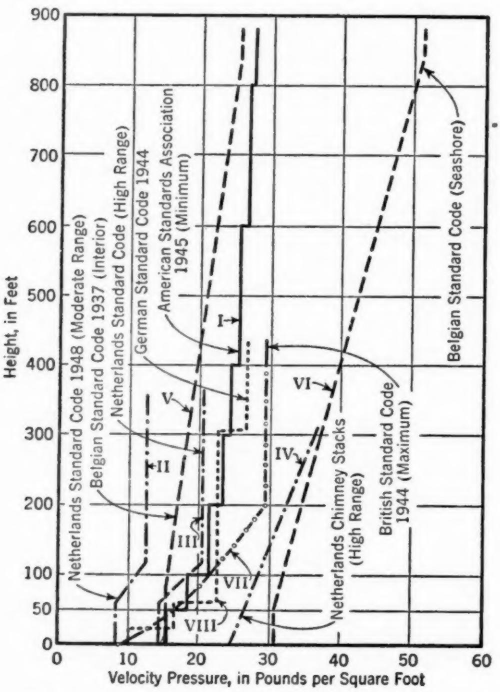


FIG. 1.—VELOCITY PRESSURES AT DIFFERENT HEIGHTS

Large-scale gusts could be particularly destructive if they occurred in a certain range, synchronous (or nearly so) with the periodicity of the structure.[4] To reach an appreciable state of resonance the wind gust would have to recur during, and synchronously with, at least a few subsequent oscillations of the structure. Such an occurrence is so improbable that it need not be considered. The periodicity of vibration of most structures is usually less than that of wind gusts (if, indeed, vibration exists at any periodicity) thus indicating the desirability of rigid types of construction with low periods of vibration.

*5. Velocity-Height Relation.*—Wind velocities depend on the geology of the locality, under consideration, and so vary in different countries; but their magnitude as a function of height above grade is the same everywhere. This basic relation between velocity (or pressure) and height has been the subject of theoretical investigation[5] as well as of experimental research. The net ex-

[4] "Vibration in Tall Stacks Solved by Aerodynamics," by W. Watters Pagon, *Engineering News-Record*, July 12, 1934, p. 41.

[5] "Wind Velocity in Relation to Height Above Ground," by W. Watters Pagon, *ibid.*, May 23, 1935, p. 742.

perience, however, as expressed in the standards of different countries varies considerably. This variation is also partly the result of simplification into formulas for practical use and partly the result of the reasons mentioned in section 4.

Velocities are expressed as pressures by the Bernoulli relation (in pound-second-feet units):

$$q = \frac{1}{2}\frac{\rho v^2}{g} \qquad (8)$$

in which $g$ is the gravity constant in feet per second.[2]

Theoretically velocity has been found to be an exponential function of height, particularly in investigations by American and German engineers. On the other hand, designers in Belgium and the Netherlands assume a linear increase with height (especially for the design of chimney stacks). For slender structures like chimney stacks the length-width ratio reaches quite an extreme, and experimental tests support the conclusion that the shape coefficient should be increased. For simplicity in adapting the code the shape coefficients in Germany and the Netherlands are maintained in their simple form without any consideration of the length-width ratio; for these slender structures a special ratio of velocity pressures, increasing more rapidly with height than meteorological data alone would warrant, has been established (see curve IV, Fig. 1).

TABLE 1.—SHAPE COEFFICIENTS FOR OPEN SHEDS (NO SIDE WALLS)

| Condition (1) | Slope of roof (2) | Windward slope (3) | Leeward slope (4) |
|---|---|---|---|
| | *(a)* GABLE ROOFS | | |
| 1 | 0° to 20° | −1.2 | −0.4 |
| | 30° and more | −0.8 | −0.8 |
| 2 | 0° | +1.2 | +0.4 |
| | 10° to 20° | +0.8 | 0.0 |
| | 30° and more | +0.8 | −0.4 |
| | *(b)* SINGLE SLOPE ROOFS[a] | | |
| .... | 0° to 10° | +1.2 or −1.2 | +0.4 or −0.4 |
| .... | 40° and more | +1.8 or −1.8 | +1.0 or −1.0 |

[a] Use the positive value when the wind is from the left and the negative value when the wind is from the right. For intermediate slopes, coefficients have to be obtained by linear interpolation.

A new principle—frequency differentiation—has been introduced in the specified basic velocity pressures in the Netherlands standard, resulting in a still greater possible degree of economy in construction, mainly for steel structures. Two ranges of basic velocity pressures have been established—a moderate range and a high range. Each range has been subgraduated according to geographic locality, which is not concerned with frequency differentiation. Experience has shown that the velocity pressures formerly accepted as standard were too high. Such pressures did occur very seldom and then only in relatively small gusts, so that the average wind load on a larger area is always less than the former standards. Therefore, a new basic moderate range of velocity pressures has been established, which is 60% of the range of velocity pressures formerly considered normal. The former standard pressures are now established in the high range of pressures. The moderate range indicates

a recurring and more or less stable loading condition (like live loads without impact) as compared with the fluctuating or dynamic load exerted by the velocity pressures in the high range. The reduced wind loads are applied in the design, retaining the normally allowed stresses (that is, tensile and bending stresses of 20,000 lb per sq in. in structural steel). At the same time the structure is designed to withstand the high range of wind load (whereby the allowable stresses for steel, for instance, are raised by a factor of 1.15). This rise is considered permissible in view of the incidental character ascribed to the high range of velocity pressures and of the relatively few times that they occur. A similar attitude, in rare combinations of loading conditions, is that of American designers who increase allowable stresses one third for the relatively rare combination of dead load, live load, snow load, and wind load.

The moderate range of wind loads is also applicable to reinforced concrete construction with the normally allowed stresses. The structure need not be designed for the high range of loads, in view of the stiffness that is characteristic of this type of construction.

For wood and masonry structures such refinement in design is not attainable and does not warrant the frequency differentiation of velocity pressures. Therefore, the old (that is, the high) range of velocity pressures has been maintained without an increase in the allowable stresses.

*6. Velocity and Direction of the Wind.*—Velocities of wind arriving from some directions usually exert greater pressures than those from other directions. For instance, in the Netherlands the following classification for velocity pressures can be made:

| Wind from | Design pressure |
|---|---|
| Northeast or east | 70% |
| North or southeast | 90% |
| All other directions | 100% |

In most standards, however, differentiation in velocity pressure according to direction is not customary.

Therefore the factors mentioned in sections 4 and 5 are the only ones that will be considered, and Eq. 3 becomes

$$q = f(t,y) \qquad (9)$$

The influences of $t$ and $y$ are usually taken as combined in one table or graph of velocity pressures for different heights above ground.

*7. Wind and Snow Load.*—Maximum snow loads and wind loads in many European standards do not need to be regarded as simultaneous. The maximum snow load may be expected with the maximum wind velocities only if a condition of solidification by thawing and subsequent freezing has made the heavy layer of snow impervious to a hurricane. On the other hand, metereological observations show that with frost the wind directions to be expected never produce maximum velocities, so that maximum snow loads and wind loads do not have to be considered simultaneously. Evidently this condition is typical only of regions with certain climatological characteristics and it is

logical therefore that a ruling to this effect appears in some countries: Belgium, the Netherlands, and Germany. The Belgian code, however, acknowledges the possibility of a combined load of snow and 40% of the maximum wind load,

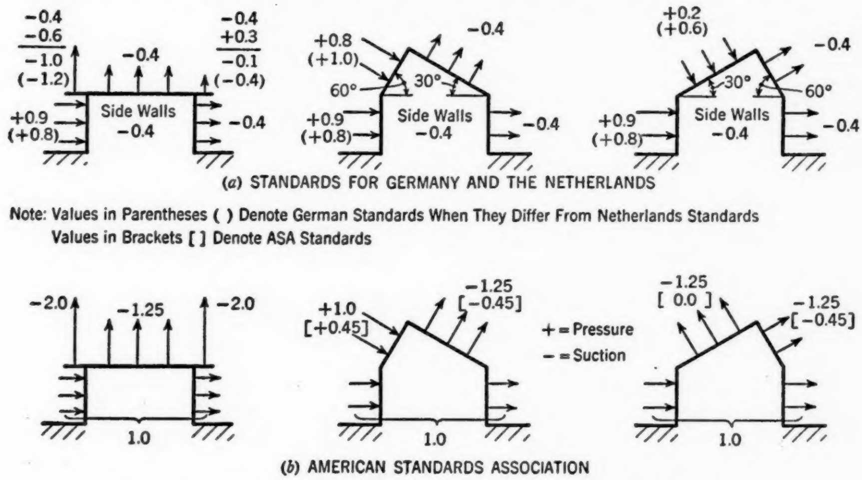


FIG. 2.—SHAPE COEFFICIENTS FOR CLOSED BUILDINGS, WIND FROM THE LEFT

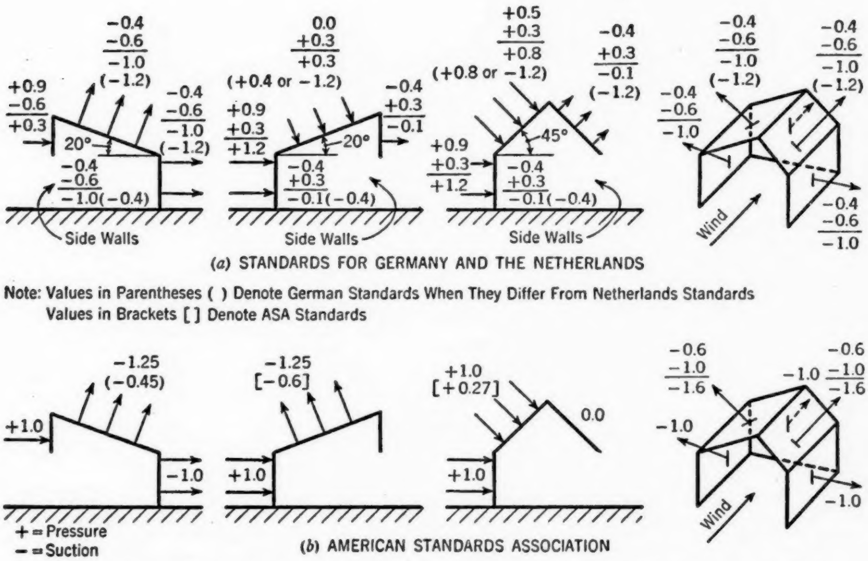


FIG. 3.—SHAPE COEFFICIENTS FOR BUILDINGS CLOSED ON ONE SIDE, USED FROM THE LEFT

whereas the German code recognizes a simultaneous existence of snow loads on roofs as steep as 45°, with maximum wind velocity. The simultaneous occurrence of full wind load and snow load is considered possible in Great Britain and the United States.

## Shape Coefficients

*8. Scale Effect, Reynolds Number, and Roughness of Surface.*—In 1914, G. Eiffel[6] showed that the distribution of pressures observed from model tests on sharp-edged bodies can be transferred directly to any larger scale regardless of velocity. In other words, there is no scale effect and the Reynolds number is 1. This is not the case for rounded surfaces (like gasholders, chimney stacks, pipes, wires, etc.), the test results of which cannot be transferred simply to larger scales. For most buildings and structures, there is no appreciable scale effect. However, a much longer time was required before it was universally understood that on a prismatic structure only the windward side undergoes pressure, whereas on all other sides suctions are exerted. By that time, also, designers had recognized the universal occurrence of vortex layers, resulting from differences between kinetic and frictional forces, in which the roughness

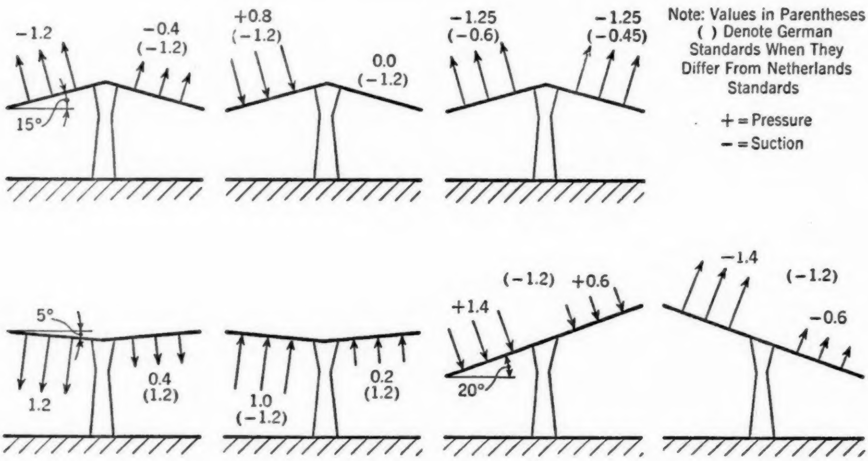


Fig. 4.—Shape Coefficients for Open Sheds, Germany and the Netherlands, Wind from the Left

of the surface plays a minor role. Thus, in the application of test results the influence of vortex layers can be disregarded, particularly in the design of angular bodies. Therefore, Eq. 5 can be simplified into

$$c = f(K) \qquad (10)$$

in which the shape coefficients $c$ are identical with $K$ for various shapes of structures.

*9. Shape Coefficients.*—The most complete set of wind-load coefficients for different shapes of buildings is to be found in standards of the Netherlands and of Germany, both arrived at independently as the result of extensive wind-tunnel tests on models. In graphic form the coefficients have been presented in Figs. 2(*a*), 3(*a*), and 4 compared with those of the ASA standards. Contrary to most standards (including those used in the United States) the German

[6] "Nouvelles recherches sur la résistance de l'air et l'aviation faites au laboratoire d'Auteuil," by G. Eiffel, Dunodet Pinat, Paris, 1914.

and Dutch specifications distinguish clearly between forces on windward and leeward surfaces, thereby localizing wind loads conveniently for structural design. As a rule the Netherlands standard is simplest in form, simplest to handle, and, at the same time, consistent with test results.

In the following tabulation, as in Figs. 2(*a*), 3(*a*), and 4, values in parentheses are the German coefficients wherever they do not agree with the Netherlands coefficients:

| Description | Coefficient |
|---|---|
| 1. Closed Buildings (see Fig. 2(*a*)): | |
| *a.* Windward Side— | |
| Surfaces with angles of inclination ranging from 90° to 65° with the horizontal | +0.9 (+0.8) |
| Surfaces with angles of inclination less than 65° if the approach angle $\alpha$, of the wind, is at that angle | $+0.02\,\alpha - 0.4$ ($1.2 \sin \alpha - 0.4$) |
| For all angles of roof, the Belgian standard requires | $\sin(\alpha + 10)$ |
| *b.* Leeward side for all roof slopes | −0.4 |
| *c.* Surfaces parallel to the wind direction | −0.4 |
| 2. Buildings Open on One Side, for at Least One Third of the Wall Area (see Fig. 3(*a*)).—When the coefficients for the exterior of closed buildings apply, the interior is subject to the following shape coefficients: | |
| *a.* If the open side is facing the direction of the wind, to a pressure | +0.6 (+0.8) |
| *b.* If the open side is away from the wind, or in the direction parallel to the wind, to a vacuum of | −0.3 (−0.4) |
| 3. Sheds Without Walls (See Fig. 4): | |
| *a.* For gable roofs, two loading conditions, 1 or 2 applied alternately, with the wind in the same direction, must be considered, giving the shape coefficients in Table 1(*a*), referring as usual to the upper side of the roof | .... |
| *b.* For inverted gable roofs (that is, V-roofs sloping toward a central valley) the same coefficients apply as for normal gable roofs (item *a*), but now referring to the under side of the roof. In both cases, the two extreme loading conditions must be taken into account to allow for | |

| Distribution | Coefficient |
|---|---|
| any possible deviation of the wind direction from the horizontal (see section 4) | .... |
| *c*. For roofs with a single slope, the coefficients in Table 1(*b*) (applied to the roof section only) are used, selecting the negative or the positive value depending on the direction of the wind | .... |
| 4. Separate Walls: | |
| *a*. For pressure and vacuum together (suction) | 1.4 (1.2) |
| 5. Open Trusses and Latticed Structures: | |
| *a*. For pressure and vacuum together (suction), applied to the area of the structure projected on the plane through the axis of the members | 1.6 |

For comparison, Figs. 2(*b*) and 3(*b*) denote the requirements of the ASA Standards for conditions similar to those in Figs. 2(*a*) and 3(*a*), respectively.[7]

## Conclusions

Although wind is a complex phenomenon, causing variable and complicated sets of loads, it has been shown possible to establish rules that are practical for actual design purposes—rules with a precision sufficient for most conditions. A general comparison between established standards in Europe and America would indicate that in some European standards a much greater refinement in the definition of loading conditions (for instance, in shape coefficients) has been sought and attained, leading to a reduction in the factor of safety and ultimately to the attainment of a greater degree of economy. This increased refinement becomes more desirable in view of the trend toward the construction of less dead load such as: Thin wall construction, light metal (aluminum) construction, prestressed concrete construction, and prefabricated construction.

However in actual practice the very common case of a structure among neighboring and partly shielded buildings often prevents an accurate forecast of loading conditions. In such cases only an investigation with actual model tests can supply definite answers; and, although the size of the project will often justify the costs of such tests, it is the time involved which prevents the undertaking of extensive tests. Available test results[8] seem to indicate that on structures consisting of a multiple repetition of units, an adjacent unit will often receive an increased rather than a reduced wind load compared to the

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[7] "Building Code Requirements for Minimum Design Loads in Buildings and Other Structures." *ASA–A58.1–1945*, Appendix 5-3.

[8] "Wind-Pressure on Buildings Including Effects of Adjacent Buildings," by Alfred Bailey and Noel David George Vincent, *Journal*, Inst. C. E., October, 1943, p. 243.

exposed unit (particularly as the result of a vacuum). Therefore the rule that no reductions shall be allowed for so-called shielded locations often does not coincide with actual conditions, which even show an increased load particularly where suction occurs.

Among phenomena about which relatively little is known are wind gusts. This wide field of research still lies unexplored. The outcome of such research might quite possibly influence and alter some of the fundamental concepts of wind loads on structures. Knowledge is still too limited on such specific details as: Size of wind gusts, horizontal as well as vertical; their spacing in the direction of the wind as well as perpendicular to it; and the velocity with which they propagate in the direction of the wind, a velocity possibly differing from that of the wind.

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